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A new type of long gamma–ray burst

Andrew King[1⋆], Emma Olsson[1] and Melvyn B. Davies[2]
[1] *Theoretical Astrophysics Group, University of Leicester, Leicester LE1 7RH, UK.*
[2] *Lund Observatory, Box 43, SE–221 00, Lund, Sweden.*

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ABSTRACT

We consider gamma–ray bursts produced by the merger of a massive white dwarf with a neutron star. We show that these are likely to produce long–duration GRBs, in some cases definitely without an accompanying supernova, as observed recently. This class of burst would have a strong correlation with star formation, and occur close to the host galaxy. However rare members of the class need not be near star–forming regions, and could have any type of host galaxy. Thus a long–duration burst far from any star–forming region would also be a signature of this class. Estimates based on the existence of a known progenitor suggest that our proposed class may be an important contributor to the observed GRB rate.

Key words: gamma rays: bursts

1 INTRODUCTION

There is now good reason to believe that a large fraction of gamma–ray bursts (GRBs) occur when rapidly–rotating massive stars end their lives and collapse to form black holes (Woosley & Bloom 2006). In some cases this event is accompanied by a supernova explosion (Galama et al. 1998; Stanek et al. 2003; Pian et al. 2006). The dynamical timescale of the collapsing core sets a lower limit to the GRB timescale, and suggests that such bursts must have long duration ($\gtrsim$ 2 s). Much of the recent rapid observational progress in this field comes from studying the afterglows which are thought to occur when matter expelled in the burst collides with its environment, which may well be matter lost by the star at earlier times. This 'collapsar' picture naturally predicts a close association between long–duration GRBs and star formation, as is observed. In a collapsar the accretion energy release is probably accompanied by explosive nuclear burning, which may expel the outer layers of the star as a supernova. While these would be undetectable at high redshift, supernovae are indeed detected in most nearby long–duration bursts.

GRBs with short ($\lesssim 2$ s) durations must instead involve the collapse or disruption of a much more compact object such as a neutron star. A plausible picture is the merger of a pair of neutron stars, or of a neutron star and a black hole (Gehrels et al. 2005; Bloom et al. 2006; Berger et al. 2005; Janka et al. 1999; Piran 1992), brought about by gravitational wave emission. Because the merger may be long delayed after their formation, such systems are neither associated with supernovae nor with star formation. Indeed the high space velocities they may acquire at the formation of one or both compact objects mean that many have travelled significant distances from their host galaxies before merging. This in turn means that there is little matter around the merger, reducing the afterglow brightness and suggesting a generally harder radiation spectrum. This may also be the reason why short–duration bursts show no energy–dependent lag in their emission, whereas almost all long–duration bursts show a correlation between peak energy and time. This is usually interpreted in terms of a more relativistic outflow, corresponding to less matter along to rotation axis in a binary merger. A supernova explosion does not occur in the merger picture of short GRBs, because the nuclear energy release per unit mass (only 6×10^{18} erg g^{-1} even for hydrogen burning, and considerably less for heavier nuclei) is far smaller than accretion yield ($\gtrsim 10^{20}$ erg g^{-1}), which is also the amount needed to expel matter to infinity from the vicinity of the accreting neutron star or black hole.

The current understanding of GRBs based on these two models thus arrives at a fairly straightforward dichotomy, in which long bursts are associated with star formation and sometimes with supernovae, and have bright afterglows, softer spectra and energy–dependent lags. By contrast short bursts should have no relation to recent star formation, be generally displaced from their hosts, and have no associated supernovae, fainter afterglows, harder spectra, and no energy–dependent lags.

While this picture has generally held up well, there are recent signs that it may not be the entire story. In particular GRB 060614 (Gal-Yam et al. 2006; Della Valle et al. 2006; Fynbo et al. 2006) is long (~ 100 s), relatively nearby (redshift $z = 0.125$), but has no evidence of any accompanying supernova, which would have to be more than 100 times

⋆ email:ark@astro.le.ac.uk

fainter than any ever observed. It also shows no energy–dependent time lag in its emission.

Here we suggest that such long GRBs without supernovae or lags may be one possible result of the merger of a neutron star and a massive white dwarf. This class of GRB is the natural outcome of a known evolutionary channel, which should contribute a significant fraction of long–duration bursts. The majority of these NS+WD mergers must be associated with star formation and lie close to the host, but a subset can occur in any type of host galaxy. Our proposed GRB channel may be very common, as the absence of a supernova can only be established in nearby bursts.

2 MERGER MODELS FOR GRBS

Were it not for its long duration ($\sim$ 100 s), GRB 060614 would closely conform to the main expectations of the usual merger picture of short GRBs sketched above. We therefore re–examine such merger models.

The basic ingredient of mergers is unstable mass transfer, i.e. the tidal lobe of the mass donor shrinks relative to that star's radius, as a direct consequence of mass transfer itself. This occurs typically when the donor/accretor mass ratio exceeds a critical value close to unity, and is a runaway process, which develops over a few times the orbital period P of the binary. A donor star fills its tidal lobe if and only if the orbital period is comparable with its dynamical time $t_{\rm dyn} \sim (R^3/GM)^{1/2}$, where M, R are its mass and radius, so this is often called the dynamical instability, and it produces typical peak mass transfer rates $\dot{M} \sim M/P$. Much of the star is smashed up into a torus surrounding the accretor. From angular momentum conservation the torus has a similar scale to the pre–instability orbit, which is itself a few times the radius of the donor. The rate at which mass now lands on the NS or BH accretor is set by the torus. As this is self–gravitating and thus subject to nonaxisymmetric gravitational instabilities, the dynamical timescale is a reasonable estimate for the burst duration, as in a collapsar.

However, dynamical instability is not confined to neutron star donors. A white dwarf donor is also subject to the instability (see e.g. van den Heuvel & Bonsema (1984), King (1988)) if it has mass $M_{\rm wd} \gtrsim 0.66 M_{\rm accretor}$. Since $M_{\rm wd}$ cannot exceed the Chandrasekhar mass $\simeq 1.4{\rm M}_{\odot}$ this requires $M_{\rm accretor} \lesssim 2.1{\rm M}_{\odot}$, and suggests that the process is most likely with a neutron–star accretor. (Note however that low–mass black holes may also be possible. Brown et al. (1996) suggest that the high–mass X–ray binary 4U 1700–37 may contain a black hole of $\sim 2{\rm M}_{\odot}$.) For a neutron star accretor mass $1.4{\rm M}_{\odot}$ we require $M_{\rm wd} \gtrsim 0.9{\rm M}_{\odot}$. A white dwarf has $R \simeq 10^9$ cm, and fills its tidal lobe in a binary with period $P \sim 10$ s, the precise value depending on its mass. As before, the white dwarf is probably totally disrupted into a torus, this time with lengthscale $\sim 10^9$ cm. As this is if anything larger than the torus likely in the collapsar picture, one would expect a similar or longer dynamical time, and thus a long GRB. As argued previously for NS+NS mergers, supernovae are unlikely if most nuclear burning occurs near the neutron star, as the nuclear energy yield is far too low to expel matter, although we shall consider a possible exception to this later. We conclude that the unstable merger of a massive white dwarf and a neutron star can produce long GRBs without accompanying supernovae.

Several NS + massive WD binaries are known in the Galaxy, as the neutron stars can be detected as pulsars. The most promising object is PSR J1141–6545 (Kaspi et al. 2000), which has a 5 hr orbit and will merge in about 10^9 yr under the effect of gravitational radiation. Because the orbit is relativistic, the masses are known to great precision (Bailes et al. 2003) as $M_{\rm wd} = 0.986 \pm 0.02{\rm M}_{\odot}$ and $M_{\rm ns} = 1.30 \pm 0.02{\rm M}_{\odot}$. This firmly establishes the mass ratio as $M_{\rm wd}/M_{\rm ns} > 0.73$, making dynamical instability and a GRB inevitable.

Davies et al. (2002) discuss the formation process for PSR J1141–6545 in detail. Starting from a pair of main sequence stars, the more massive primary fills its Roche lobe as a giant and transfers its mass to the companion, which then becomes more massive than the primary was originally. The core of the primary becomes a massive white dwarf, while the companion is now massive enough to become a helium star. This star eventually fills its Roche lobe and transfers its envelope to the white dwarf at a high rate, causing most of it to be ejected from the binary, which shrinks. Ultimately the helium star explodes as a supernova, producing a neutron star in the required tight orbit with the massive white dwarf. Davies et al. (2002) estimate a formation rate of $5 \times 10^{-5} - 5 \times 10^{-4}$ yr^{-1} for such systems in the Galaxy (their Fig. 8) and further show that over half of them merge within 10^8 yr, and 95% within a Hubble time (their Fig. 10).

This suggests that such systems can indeed make a significant contribution to the gamma–ray burst rate in the Universe. Davies et al. (2002) also compute the distribution of supernova recoil kick velocities for these systems (their Fig. 9). A substantial fraction have relatively small velocities $\lesssim 100$ km s^{-1}. This is promising for models of GRB 060614, as this and the merger timescale distribution suggest that in many cases the GRB must occur with the system still relatively close to the host galaxy, as observed for GRB 060614 even though the host is a dwarf. Together with the high initial merger rate (100 times higher in the first 10^8 yr) this shows that NS + massive WD bursts must show a strong correlation with star formation, although the relatively rare later mergers would show no such correlation.

We have mentioned that an accompanying supernova is unlikely if nuclear burning occurs close to the neutron star. The one possible escape from this conclusion would occur if it were possible to initiate burning at much larger distances. We note that since the merger contains no H or He such supernovae would automatically be of Type Ic, as indeed observed for GRB supernovae. However this possible supernova mechanism is probably ruled out for white dwarfs sufficiently massive to have ONeMg rather than CO composition ($M_{\rm wd} \gtrsim 1.1{\rm M}_{\odot}$), because neutrino energy losses through electron capture (particularly on Mg) (see e.g Nomoto et al. (1979)) prevent explosive burning.

We note that Fryer et al. (1999) suggested that NS + WD mergers might not produce GRBs. They reasoned that the neutron star might build up a spherically symmetric atmosphere, which could make a spherical explosion from the surface baryon–rich, and therefore sub–relativistic. This is evidently a less serious problem for an explosion directed along the rotational axis, as is now usually assumed to be the case. A related question is whether the accretor survives as a neutron star rather than collapsing to a black hole early in the hyperaccretion phase. The total mass $\simeq 2.3 M_{\odot}$ of PSR J1141–6545 is lower than some theoretical estimates of the maximum neutron–star mass (e.g. Kalogera & Baym (1996)) and probably less than the mass potentially reached by neutron stars in some low–mass X–ray binaries, but calculations of NS+NS mergers generally lead to early collapse to a black hole (e.g. Rosswog et al. (2003)). The accretion yield on a neutron star is $\sim 10\%$, comparable with all but the most rapidly–spinning black holes (42%). Evidently there is sufficient energy release to power a gamma–ray burst in both cases, but a late collapse to a black hole would presumably cause a second energetic event (similar to the supranova model of Vietri & Stella (1999), where angular momentum loss rather than continued accretion drives the collapse). This is conceivably interesting in connection with the late flares seen in some GRBs, e.g. GRB 050502b (Burrows et al. 2005)). One possible discriminant between the two cases might be the properties of the jets needed to make the gamma–rays, but we note that neutron–star X–ray binaries are apparently able to make jets too (cf Migliari & Fender (2006)).

3 CONCLUSIONS

We have suggested that GRB 060614 is representative of a new class of gamma–ray burst in which a massive white dwarf merges with a neutron star. The characteristics of this class are clear. They are long–duration GRBs, in some cases definitely without an accompanying supernova, which may show some other features usually associated with short bursts, such as a lack of energy–dependent time lags and perhaps much weaker afterglows.

As a class these bursts show a strong correlation with star formation, and occur close to the host galaxy. However rare members of the class need not so correlate, and can have any type of host galaxy. Thus a detection of a long–duration burst far from any star–forming might be a signature of one of these bursts.

Our estimates based on PSR J1141-6545 suggest that this proposed type of GRB may provide an important fraction of the observed GRB rate. We note that the absence of a supernova can only be established in nearby bursts.

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